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Reusability and recyclability of plastic cosmetic packaging: A life cycle assessment

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ABSTRACT

The importance of product sustainability has become increasingly relevant, with several key stakeholders striving to improve the lifecycle environmental footprint of their products in various aspects. This sense of sustainable urgency has also been felt in the cosmetic industry, which contributes significantly to the global plastic manufactured and used worldwide. Design for Recycling and Design for Reuse are two different approaches which can be employed separately or concurrently. When designed for reuse, products are typically more robust in order to increase their probability to be used more than once. If reuse is not possible, it is essential that dematerialisation and recycling are applied. This study assessed the environmental impacts resulting from reusable, recyclable, and dematerialised plastic cosmetic packages, and attempted to answer the primary question: Is it more sustainable to design an extremely durable product that can be reused several times, or to apply dematerialisation but consequently create a less robust product which allows for less reusability potential? Life cycle assessments of different versions were conducted, to identify what features are responsible for such impacts. Findings showed that the positive effect of reusability out ways by far the effects of dematerialisation by 171%, and that removing resourceful materials which render the package to be reusable, resulted in a 74% reduction in environmental impacts only when the packaging materials are fully recycled. This study concludes that in such cases, reuse should be given prominence, as recycling would only depend on the user and the infrastructure in place.

1. Introduction

Changing times have brought along a sense of urgency towards sustainability and a cleaner way of living. In recent years sustainability has become a key trend, with awareness on recycling everyday products and minimising energy consumption becoming the norm in the average consumer's household. However, the hidden mountain of resource consumption will not necessarily be solved by making products greener and more sustainable, and will require thorough collective thinking to change the core supply system and infrastructure currently in place.

1.1. Packaging in the cosmetics industry

The cosmetic industry has a very heavy impact on packaging. In 2017, the global cosmetic industry was valued at USD 532 billion, with forecasts estimating this valuation to reach USD 863 billion by 2024 (Zion Market Research, 2018). Of this USD 532 billion, approximately USD 25 billion was reflected in product packaging, showing just how large of an impact the packaging aspect has in this industry (Zion Market Research, 2018).

When discussing packaging in the cosmetic industry, it is important to differentiate the terms packaging and secondary packaging. In cosmetics, 'packaging' refers to the primary packaging aspect, i.e. the container housing the cosmetic substance, whilst 'secondary packaging' refers to the additional layers of packaging which are sometimes present for branding and logistical purposes. Both primary and secondary packaging are commonly found in significantly high and sometimes even excessive quantities, which are not really needed but help to create a more premium experience such as by including thick ribbons, individually packing items, or including lots of paper separation packaging. In fact, more than 120 billion units of cosmetics packaging were recorded to be produced globally in 2018 (Moore Kaleigh, 2019). Moreover, studies show that a significant lack of recycling is taking place, with a 2018 EU investigation showing that 41.5% of the generated plastic waste in Europe is recycled, with the rest being deposited in landfills or being used solely for energy recovery (Eurostat, 2021).

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Cosmetic companies, and other companies in general are setting ambitious sustainability goals. L'Oréal and Unilever both stated that they aim to make 100% of their packaging reusable, refillable, or compostable by 2025 with L'Oréal aiming to source 50% of the packaging material from recycled plastic, and Unilever aiming to source 25% (Alejandra Borunda, 2019). LUSH cosmetics managed to improve its environmental footprint by implementing design changes such as reducing product thickness and replacing standard wrapping paper with reusable fabric wrapping made from recycled plastic (Europen and ECR Europe, 2009). LUSH also claim that 35% of their physical outlet product range do not need any packaging whatsoever, and when secondary packaging is necessary, LUSH have switched to using reusable product packaging by using aesthetic and durable plastic boxes. These can be reused by either using them to resend another gift in them, or to organise jewellery or small items (Lush Cosmetics, 2019).

1.2. Packaging materials used in cosmetics

The three main materials used for cosmetic packages are plastic, glass, and metal, with foil and acrylic typically being used as secondary materials for decoration purposes (Sahota, 2013). Once again, the most common material used in cosmetics is plastic, more specifically thermoplastics. The main advantages of using plastic in cosmetics include high quality, flexibility, and resistance to breakage which is extremely useful for distribution. Using plastic is also extremely light, relatively cheap, and odourless. Common polymers used for cosmetic containers include polyethylene, polypropylene, acrylonitrile butadiene styrene and polyvinyl chloride, along with other special polymer processing additives such as Kynar Flex PVDF (Arkema Inc, 2021). This additive is added in the order of 0.02% – 0.08% with respect to weight and helps enhance overall mechanical properties and improve surface defects (Kröhnke, 2012). It should be noted that cosmetic packaging should be free of substances that can react with the chemicals in the product itself and create hazardous substance. Common disadvantages of using plastic in cosmetic products include stress cracking, poor impact resistance, and crazing (Shivsharan et al., 2014).

1.3. Sustainability in manufacturing

One of the primary methods for sustainable manufacturing is to design with the environment in mind. This is done by using Design for Environment (DFE) principles in the entire life cycle of the product. The thought behind employing DFE principles is to ensure environmental sustainability whilst also allowing for economic growth and increase in production (Fiksel, 2009).

1.3.1. Designing for reusability

The term reuse is defined by Article 3 of the 2008 European Waste Framework Directive (2008/98/EC), as "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" (European Commission, 2008). Reusability can cover a wide spectrum of small to very large products, and it is necessary to understand the different categories, as each category is responsible for different levels of environmental impacts. Remanufacturing is one such category and can be described as the industrial reuse of products or components. It should be noted that remanufacturing requires energy in order to restore a product at its End-of-Life (EOL) to a useable condition. However, the savings registered when remanufacturing are quite significant when compared to standard manufacturing (i.e. the production of a new product using virgin raw materials), as was shown by Cooper and Gutowski's extensive analysis. They found that the energy savings registered when considering remanufacturing is substantial and varies significantly from one product to another (Cooper and Gutowski, 2017).

A preliminary LCA study carried out by Hamade et al. determined the effectiveness of reusing PET bottles (Hamade et al., 2020). Hamade et al. uncovered that a single reuse of a standard 500 ml water bottle would save around 1 MJ in processing energy, and 33 g of CO_2 per bottle, as opposed to having to manufacture such a bottle from scratch. Moreover, when they compared a single reuse of the same PET bottle to the recycling EOL option, they found that this would result in approximately 74% energy savings, and 182% less CO_2 production in favour of reusability (Hamade et al., 2020).

Another interesting case study can be observed by Danish makeup brand Kjaer Weiss. Founder Kirsten Kjaer knew that her makeup brand would differentiate from others by planning her makeup cases to be refillable (making them reusable), whilst still keeping the premium luxury tag. Kjaer Weis shows that refilling a reusable compact is easily done directly by the consumer, by dislodging the empty cosmetic cartridge and swapping in the replacement cosmetic refill tray (which is 30% cheaper than purchasing a brand new compact) into the compact case. They have also managed to make versions of mascara, lip gloss, and eyeliner that are refillable, which in total contribute approximately 25% to the business's annual revenue (Kjaer Weis, 2021).

1.3.2. Designing for recyclability

Recycling is defined as the process of recovering material from a product at its end of life, in order to be reused in a new application as opposed to the conventional waste disposal method. This houses several benefits such as slowing down the rate at which natural resources are harvested by incorporating existing materials, reducing the total waste sent to landfill, and reducing energy resources ("How can Recycling Materials lead to Environmental Sustainability?," 2019). Despite these benefits, recycling is still not the most popular EOL option worldwide, due to issues associated with limited economies of scale, and potential contamination at the product's EOL, which may render a product difficult to recycle.

It is also important to note that not all plastic is recycled equally, which is why a global recycling category system named as the Resin Identification Code (RIC) has been setup by the Plastics Industry Association in order to categorize the different plastics commonly available. PET, HDPE, and PVC are commonly recycled, whilst PS, PP and LDPE are not, because they tend to get stuck in recycling machines during the sorting process (LeBlanc Rick, 2020).

Others are also considering using recyclable natural polymers. Sid et al. reviewed different plastic packaging substitutes revolving around biodegradable plastics, and stated that although there are still a number of issues that are currently being faced (such as high manufacturing costs), such packaging will become commonly utilised in years to come (Sid et al., 2021). Zhang et al. also researched recyclable polymer composites, specifically focusing on food packaging. They found that biodegradable polymers can be used for food packaging, as long as such packaging can be ensured that it is safe, which is currently not always the case. Further research and development is required in this area (Zhang et al., 2022). It should be noted that no specific studies highlighting this topic in the cosmetics industry were found.

2. Materials and methods

The primary objective of this study is to quantify and compare the different environmental life cycle impacts resulting from recycling and reusing plastic cosmetic packages, and to identify the best solution for the manufacturing of such products. This was achieved by utilising an extensive LCA study based on a case study product produced by Toly Group. The LCA software used in this study was SimaPro 8.4. which allows analysis of complex life cycles in a simple and transparent way (Sima Pro, 2020a). It also allows for the complete customisation of processes which allows an increased level of accuracy.

2.1. LCA methodology

The main points of the LCA study in relation to the proposed methodology shall be described in detail below, in their respective section. A life cycle assessment is an ISO standardised methodology (ISO 14,040 and ISO 14,044) that is commonly used to evaluate all life cycle stages of a product, from the raw material extraction stage to the product's end of life. Consequently, this is why LCAs are often referred to as following a 'cradle to grave' approach.

2.1.1. Goal and scope definition

The main goal for this study is to study the environmental impacts of different variations of plastic cosmetic packages and propose environmentally conscious possibilities. The scope of this study is to show how the defined goals can be met with the limitations that are in place. This is done by clearly defining the product system of the study. In summary the proposed main takeaways for this analysis were to compare the total life cycle environmental impacts of reusable and recyclable cosmetic packages, and to determine whether designing for reusability or designing for recyclability should be given prominence when considering plastic cosmetic packages. This was attempted by varying different parameters in order to evaluate how different variables compare with each other and determine what the most environmentally conscious packaging option would be.

A case study cosmetic package (blush compact) which is shown in Fig. 1, was selected and used for the analysis. This product is a small blush powder makeup compact, intended for portable everyday use. The design is relatively simple with the product possessing a circular shape and a pinned hinge design. The main parts that constitute the case are the lid, mirror, base, base plate, and pin. The circular mirror is glued to the inside of the case's lid, and the pin constrains the rest of the components together. The main materials include acrylonitrile butadiene styrene (ABS) for the main housing of the case (i.e. lid, base, and base plate), glass for the mirror, and stainless-steel for the pin that acts as the pivoting hinge. The cosmetic powder itself is contained in a circular aluminium container defined as the pan. This makes the product reusable, and users can easily purchase additional pans from retailers once their existing pan has been used up and swap out the old with the new refill whilst keeping the same compact case. An important clarification that shall be defined for the reader's ease of understanding, and that will be used throughout, is the difference between case and compact. The term case refers to the full assembly of the cosmetic case but without housing the pan (i.e. one empty case). On the other hand, the term compact refers to the final end product which is sold to consumers (i.e. compact = case + pan). The cosmetic powder itself was excluded from the analysis as this study is only focussing on the packaging components.

Since this is a cradle to grave LCA, all stages of the entire life cycle of the product were taken into consideration. The first stage is the raw material extraction stage, which considers the raw materials, water usage, and energy consumption required to create the base necessary for the cosmetic blush. The powering of the extraction plant as well as any transportation needed to transport raw material to the initial processing plant were considered. The manufacturing stage encompasses the processing of all the sourced raw materials, as well as the final assembly of the compact case. The main process utilised at the manufacturing facility is plastic injection moulding to manufacture the lid, base, and baseplate components. The other manufacturing process is the cutting of flat glass mirror sheets into circular disk shapes, by utilising a CNC diamond cutter. The mirror is glued onto the lid by first applying the adhesive onto the lid, then polishing the mirror, and finally combining the two parts together by using a pressing process. A decorative foil is hot stamped in two phases, first by applying the foil print throughout the outer circumference of the lid, and then by printing an artwork text on the foil. Finally, the pin component is attached semi-automatically, by first having a machine feed the pins through a vibrator bowl into a shuttle, in order to align the pins with the pinholes. Once this step is complete, an operator places the lid, base, and baseplate components in their required position, and then activates a mechanical switch to complete the pin insertion, thus rendering the case as being fully assembled.

Fig. 1. Tivoli cosmetic blush compact.

Once the case is assembled, it is shipped to a filler company whose job is to load an aluminium pan filled with cosmetic blush in the case, as well as insert several promotional material. Once this stage is complete, the filler company sends the consignments to a global distribution centre from where the products are shipped to retailers around the world. Transportation types and distances were researched and calculated to provide an increased level of accuracy to the overall generated results. The compact's use phase starts when the end consumer purchases the products from a retailer. It should also be noted that the studied product does not have any secondary packaging, and the product is typically sold as manufactured, i.e. with the case as the primary packaging housing the cosmetic powder. The main aspect related to the use phase in this study is reusability. By continuing to reuse the existing case and utilising pan refills to reuse the cosmetic compact, the use phase is extended. Finally, once the compact's powder blush is finished or when the product reaches its end of life, the product enters its disposal stage. In this study two main scenarios are considered for this stage, which are recycling or landfilling, at different rates.

It should be clarified that only the case was considered for the End-of-Life (EOL) scenarios, since the pan was always considered as being sent 100% to landfill. This is because the pan is not easily recyclable considering that it will always be contaminated with some cosmetic powder. With regards to what parts actually get recycled, it is assumed that all plastic ABS parts i.e. the lid, base, and baseplate, will be recovered and reground to form part of a new ABS plastic mix. On the other hand, the mirror part is assumed not to be directly reusable, since this part is relatively fragile and may be recovered in a broken state. A number of drawings related to the existing product design can be observed in Fig. 2.

2.1.2. Functional unit

A clear functional unit needs to be established when carrying out an LCA study, as this is a quantitative measure of the function of the system being studied and allows for fair 'like with like' comparisons (Alejandra Borunda, 2019). One such comparison can be observed in a study analysing eco-design packaging configurations in an attempt to reduce environmental impacts. The functional unit was defined as the packaging and transportation of 1 kg of detergent, in order to allow for fair comparisons to be made solely with the packaging itself (de Lapuente Díaz de Otazu et al., 2022).

With reference to the cosmetic blush compact shown in Fig. 1, surveying 20 cosmetic blush users showed that a 3.5 g cosmetic powder pan lasts for around 100 uses (Westervelt, 2018). If the user uses the blush powder once a day (i.e. 1 day = 1 use), the user will require approximately four cosmetic pans per year. The probability that the user will not keep buying refill pans or may wish to change brand increases significantly after 1 year. The functional unit for this study comprised the packaging and transportation required to contain the cosmetic powder used in the period of one year by one person. Quantitatively, this

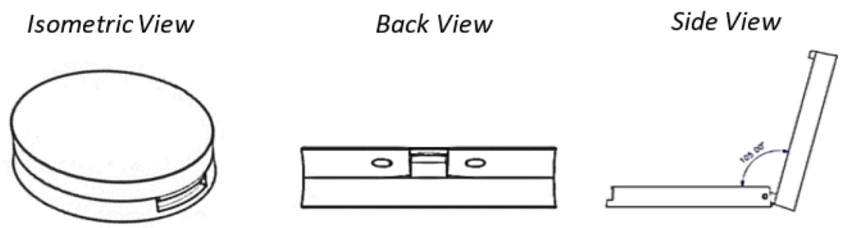

Fig. 2. Existing product drawings.

is defined as **the packaging required to provide the user with** 14 g **of cosmetic blush powder** i.e. 4 pans of 3.5 g of cosmetic powder each. By defining this functional unit, this allows the researcher to keep the expected output quantity of cosmetic powder to remain constant, whilst being able to compare different versions of compact cases in a fair method.

The system boundaries for this LCA study can be observed in Fig. 3, which highlights the full life cycle process described in Section 2.1.1. It should be noted that the production of the cosmetic powder, as well as the purchasing of the cosmetic compact by the user from the retail outlet, have been excluded from the system boundaries since they are beyond the scope of this study.

2.1.3. *Inventory analysis*

In the inventory analysis stage, all the required data necessary to model the LCA was researched and/or calculated. The full bill of materials of the existing blush compact is tabulated in Table 1, along with the relevant manufacturing processes utilised for each part. The data shown is for one compact. The material required per Functional Unit varies according to the various versions which are explained in Tables 2 and 3. Data relating to the embodied and processing energy utilised for each part were also included in this table, with such information being extracted from Ansys Granta EduPack (Ansys (CES), 2021). It should be clarified that the cosmetic blush powder was only considered in terms of its mass, in order to maintain the actual total product mass accuracy. Intrinsic effects due to the powder itself and manufacturing of the powder were omitted from this study, as they were not within scope.

2.1.4. *Methodology review*

The primary parameter analysed in this study is the Number of Case Reuses which relates to the reusability aspect, as by continuing to reuse the existing case and utilising pan refills to reuse the cosmetic compact, the product use phase is extended. In the default version, V1 in Table 2, it is assumed that the case detailed in Table 1 is used 4 times (first use and three reuses). In V1A the case was dematerialised by 7% which led to a less robust product, and in turn allowed for less reusability. In version V2, this concept was applied and extended to create a single use product, the mass of which was reduced by 17% when compared to the default scenario.

Version V3 is a fully recyclable single-use product while in V3E the

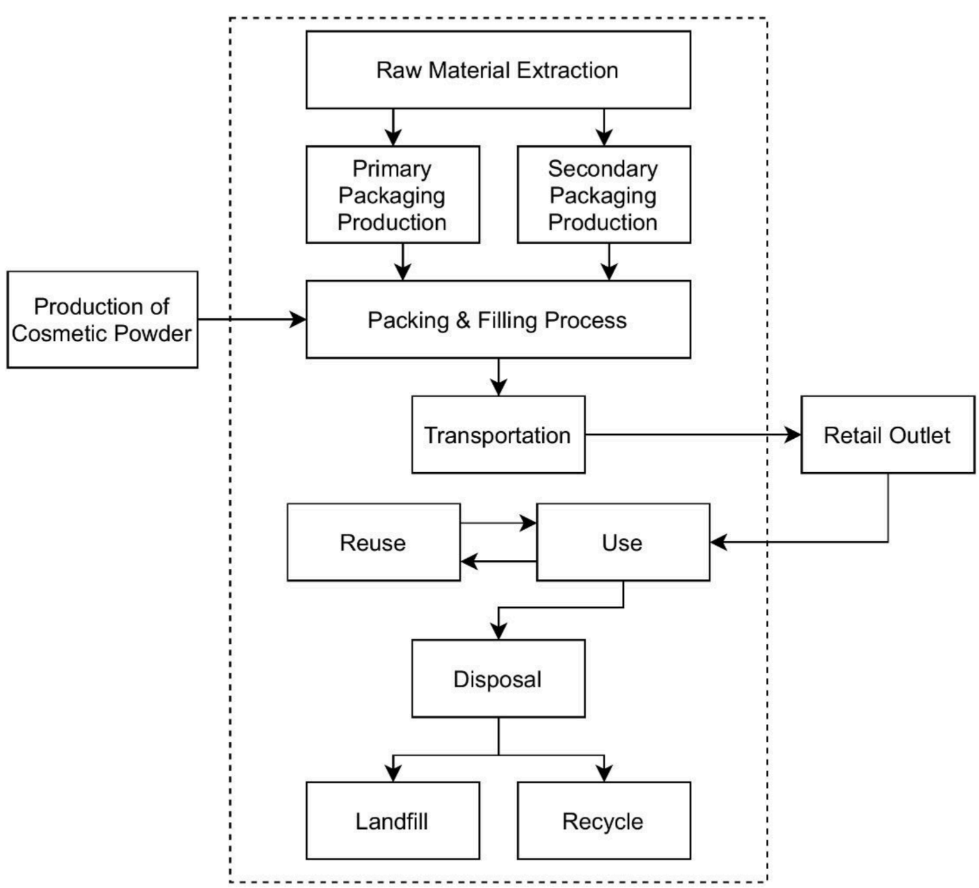

Fig. 3. System boundaries definition.

Table 1
Compact bill of materials (* excluded from LCA) (Ansys (CES), 2021).

Part	Raw material	Manufacturing process	Mass (g)	Embodied energy (kJ/Part)	Processing energy (kJ/Part)
Lid	ABS HI121H	Injection Moulding	5.52	587.9	104.6
	Adhesive Resin	Stock Part	0.05	4.50	0.30
	Aluminium Foil	Hot Stamping	0.05	10.2	0.30
Mirror	Silver Coated Glass	CNC Diamond Cutting	5.94	118.8	46.6
	Adhesive Resin	Stock Part	0.50	45.0	3.0
Base	ABS P2HAT/792	Injection Moulding	2.47	263.1	46.8
Base Plate	ABS P2HAT/792	Injection Moulding	4.17	444.1	79.0
Pin	AISI304 Stainless Steel	Deep Drawing	0.10	6.4	1.6
Pan (Full)	Cosmetic Blush Powder*	Stock Part	3.50*	0.0	0.0
	Aluminium Alloy (Pan)	Stock Part	2.30	466.9	14.0
Total			**24.6**	**1946.9**	**296.2**

Table 2
List of version classifications.

Version classifications	Description
V1	Existing benchmark version with a max reuse capability of 3 times
V1A	Version applying a dematerialisation rate of 7%, consequently reducing the max reuse capability to 1
V2	Version applying a dematerialisation rate of 17%, consequently reducing the max reuse capability to 0
V3	Version eliminating the use of the pan altogether, by having cosmetic powder inserted directly into the case. This removes any potential for reusability
V3E	Version prioritising sustainability over build quality by applying a dematerialisation rate of 17% and replacing the pin with a clip-on hinge

plastic components are dematerialised and the steel component is removed. For all versions considered, the manufacturing country and End-of-Life (EOL) country parameters were kept constant as Malta, and the European Union respectively.

2.2. Proposed versions

The proposed packaging alterations, allowing for the identification of the features responsible for the environmental impacts being studied are summarised in Table 2. Further details on each version classification is included in this table.

Table 3 shows a more detailed explanation of the proposed versions. The terminology (a), (b) and (c) refer to the three different recycling rates of 0%, 50% and 100% respectively. It was assumed that the pan which would be contaminated with cosmetic powder, and the glass mirror are landfilled.

Version V1(a), is the existing cosmetic blush product with an assumed reuse capability of 3 times, i.e. 4 uses in total. This version shall be considered as the main benchmark against which all other versions shall be compared. Additionally, two other versions (V1(b) and V1(c)) were considered where it was assumed that V1(a) remains as is, but with the added difference of a recycling rate of 50% and 100% respectively. This makes V1(b) and V1(c) both reusable and recyclable simultaneously. The only design changes that were applied to the benchmark version, was to swap the steel pin with a plastic pin, and to attach the mirror by utilising snap fits instead of adhesive in order to incorporate design for environment principles and facilitate the disassembly and recycling process.

Version V1A, also builds upon the existing product benchmark, but applies 7% dematerialisation to all the plastic ABS parts, i.e. the lid, base and baseplate. This reduces the product's mass, and in turn also reduces the overall durability of the product. Therefore, it was assumed that the reuse capability decreased, allowing only for the potential of one reuse. Hence, when considering the functional unit, 2 cases and 4 pans were required.

Version V2 also builds upon the benchmark cosmetic blush product design, with the main difference being the 17% dematerialisation to all plastic ABS parts. It should be clarified that the dematerialisation was applied to all plastic parts, i.e. lid, base, and base plate, and that the percentages were generated by assuming the lowest part thickness possible all around to be 1.25 mm as opposed to the benchmark thickness of 1.5 mm. This value is the minimum possible thickness that can be used (as confirmed by the manufacturing company) in order to maintain a functioning product. However, this dematerialisation also contributes to two additional aspects. The first is that the product is too flimsy to be reused and can only serve a single-use function which makes the compact a single-use product. Consequently, this results in a product that is neither reusable nor recyclable, since an adhesive which is considered as a contaminant is used and since the pin hinge mechanism makes it difficult to disassemble. The second aspect is that the perceived customer quality is now considered as extremely low.

Version V3, considers a product with a single use capability, and a fully recyclable end of life disposal scenario. In order to manage this, the design of the product had to differ significantly from the other versions. The first change involved changing the steel pin to a plastic ABS pin, as different materials provide material sorting difficulties when disassembling, and it is recommended to have all parts of an assembly made from the same material whenever possible. The new pin was assumed to be

Table 3
List of methodology versions.

	V1 (a)	V1 (b) (c)	V1A (a)	V1A (b) (c)	V2	V3 (a)	V3 (b) (c)	V3E (a)	V3E (b) (c)
Features	Reusable	Reusable + Recyclable	Reusable + Demat.	Reusable + Recyclable	Single Use + Demat.	Single Use	Single Use + Recyclable	Single Use	Single Use + Recyclable
Case Demater-ialisation	/	/	−7%	−7%	−17%	/	/	−17%	−17%
Reuse Capability	3	3	1	1	0	0	0	0	0
Hinge	Steel Pin	Plastic Pin	Steel Pin	Plastic Pin	Steel Pin	Plastic Pin	Plastic Pin	Clip-on Hinge	Clip-on Hinge
% Plastic Recycle	0%	50%, 100%	0%	50%, 100%	0%	0%	50%, 100%	0%	50%, 100%
Pan Design	Reusable	Reusable	Reusable	Reusable	Glued Pan	No Pan	No Pan	Non-Reusable	Non-Reusable

14 mm long with a diameter of 1.4 mm, as opposed to the previous steel pin of 12 mm and diameter of 1.2 mm, in order to add a safety factor to the pin's sturdiness. This resulted in reducing the mass of the pin from 0.1 g to 0.026 g, even though the overall volume was increased by 58%. Additionally, this scenario was considered to be a single use product. This was done in order to be able to compare reusable versions with a single use, recyclable product. Finally, the last feature to note is that this scenario differs slightly from all the other scenarios because it features a different pan design. In this version, the aluminium pan is excluded from the compact, with the blush powder being assumed to be loaded directly into the case cavity itself. This feature was considered in order to study how removing the pan element completely effects sustainability. Consequently, this requires a sturdier and more robust case, since the powder packing process is significantly demanding, as informed by the manufacturers themselves. Hence, no dematerialisation was applied in this scenario, as otherwise the product would have resulted in not being sturdy enough to withstand the powder packing process. It should be noted that this proposed design change requires comprehensive stress analysis before implementation, in order to confirm that the proposed design is actually technically viable in a real-life application. This applies to all the proposed scenarios apart from V1 since this version already exists.

Finally, Version V3E can be considered as the eco-friendly version prioritising sustainability over build quality by trading the standard pin hinge mechanism to a clip-on hinge, which is deemed as poor quality from a consumer point of view. The main advantage that this design change has is that it drastically improves the disassembly process when recycling, whilst simultaneously removing an additional part, even though the pin part is almost negligible in terms of mass and environmental impacts. This version has the maximum dematerialisation rate of 17% applied with no reuse capability, as well as being recyclable. The premise behind this version is that it can be marketed as being the most environmentally friendly blush product, albeit the quality of the case being extremely poor. A detailed summary of all the proposed versions is presented in Table 3 below.

A table comparing how many cases and pans are required for the proposed versions to satisfy the defined functional unit, can be observed in Table 4. The total product mass required to satisfy the functional unit is also displayed in this table for indicative purposes.

2.2.1. *Impact assessment*

The Life Cycle Inventory database used in this LCA was Ecoinvent 3, which is a comprehensive database with more than 15,000 datasets (Sima Pro, 2020b). The chosen method was the ReCiPe 2016 endpoint method (Hierarchist version), which is the default ReCiPe endpoint method (Sima Pro, 2020b). The main impacts which were assessed in this LCA study revolve around two of the primary ReCiPe endpoints, which are the Human health and Ecosystems endpoints (Ellen Meijer, 2014). The Human health endpoint covers the impacts associated with several diseases and malnutrition, while the Ecosystems endpoint covers damage associated to freshwater species, terrestrial species, and marine ecotoxicity amongst others.

Table 4
Functional unit mass comparison.

	V1 (a) (b) (c)	V1A (a) (b) (c)	V2	V3 (a) (b) (c)	V3E (a) (b) (c)
No. of Cases	1	2	4	4	4
No. of Pans	4	4	4	0	4
Cosmetic Blush Powder (g)	14	14	14	14	14
Total Mass (g)	**42.0**	**59.2**	**90.5**	**86.7**	**87.7**

3. Results interpretation and discussion

This section will review the results generated from the LCA study, following the methodology above. It should be noted that the presented results all represent the environmental effects of the functional unit defined previously.

3.1. *LCA results*

First, the existing benchmark version V1(a), was analysed on a part-by-part basis in order to identify how the different parts contribute to the chosen impacts, as can be seen in Fig. 4. The human health endpoint was considered, along with the global warming midpoint. It should be noted that this chart has been normalised with respect to the highest contributor (i.e. the Pan) in order to obtain a clearer visualisation of how the results compare.

As can be observed by the human health indicator, the biggest impact is caused by the pan. This is primarily attributed to the material selection, because aluminium as a raw material has much worse environmental impacts than ABS, glass, or steel. In fact, the aluminium pan has a larger CO_2 footprint and increased water usage than the lid, even though its mass is lower than that of the lid. However, interestingly when observing the global warming midpoint, the lid scored a slightly higher environmental impact then the pan. It should be clarified that the endpoint is an accumulation of a number of different midpoints, and that not all midpoints reflect the result of the final endpoint.

The base plate and base rank in sequential order depending on their mass, since the material and processes used remains constant throughout. Interestingly, the mirror proved to have a lower environmental impact than the ABS parts even though this component has the highest mass ratio of the entire product. However, once again, the difference between the specific environmental impacts is significant. Finally, the steel pin proved to cause an almost negligible impact, due to its extremely low mass.

3.2. *Version comparison*

The resulting comparisons of all the versions along with their respective recycling subcategories are shown in Fig. 5. The results were normalised with respect to the existing version, V1(a), for both endpoints, as this was treated as the benchmark. It should be noted that similar to other LCA studies carried out, there is a level of inaccuracy in the generated results. A 10% margin of error is overlayed on the results in Fig. 5.

V1 vs V1A

When comparing these two versions together, the only difference is the dematerialisation of 7% to all plastic ABS parts. It is evident from the comparison in Fig. 5 that V1 is the more sustainable version even when considering the 10% margin of error, with an average decreased environmental footprint of 39%. This is interesting when considering that V1A is dematerialised by 7%, meaning that although V1A requires less material to produce, it is less sustainable overall when considering the reusability aspect.

V1 vs V2

When comparing these two versions together, the only difference is the dematerialisation of 17% to all plastic ABS parts. The results evidently show that V1 is by far more sustainable than V2 with a decreased environmental footprint of on average 180% for the two endpoints. This result again confirms the significant positive effect of reusability as opposed to dematerialisation (and the resulting loss in quality and lifetime reduction), which is especially interesting when considering the overall functional unit mass as can be seen in Table 4. This shows that even with V2 having an applied plastic dematerialisation rate of 17%, it still requires an additional 48.5 g of product material when compared to the benchmark (V1), with no dematerialisation. Therefore, the key takeaway from this comparison is that it is more

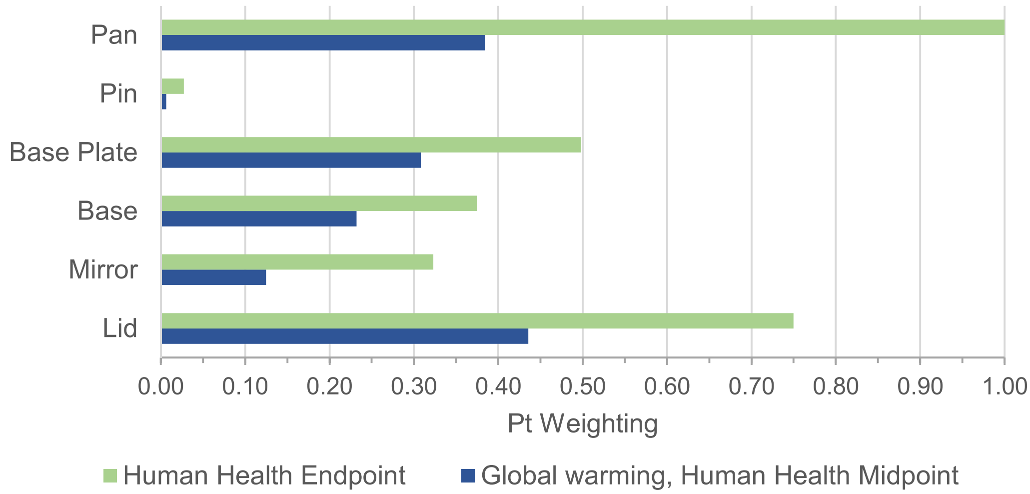

Fig. 4. V1(a) Part analysis.

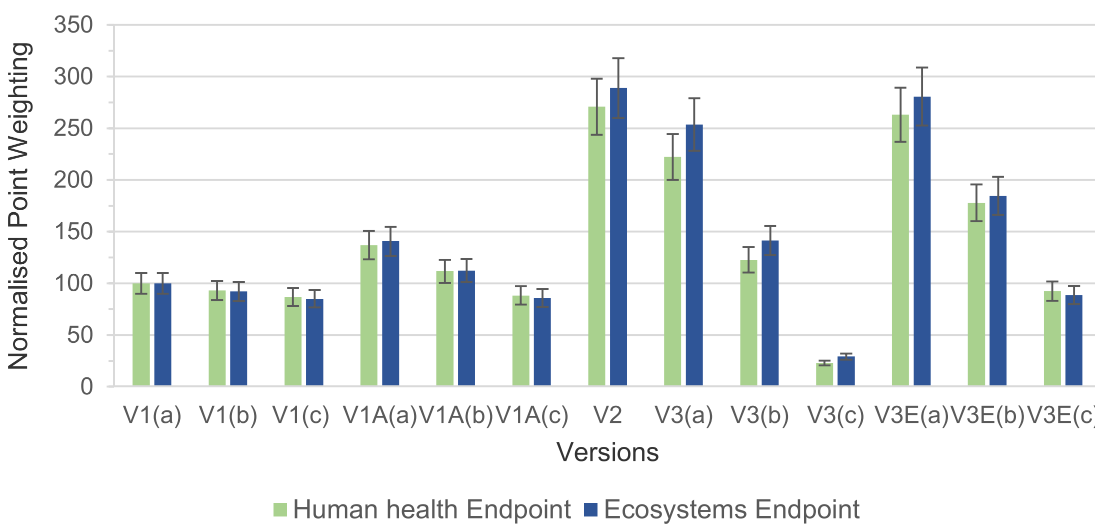

Fig. 5. Normalised endpoint life cycle impacts of the different versions (V1(a) = 100).

environmentally friendly to reuse rather than dematerialise and consequently reduce the reuse capability.

V3 vs V3E

There are two main differences between these two variables. The first is that V3 is the only version that does not need to utilise the pan component, as the product's design allows the cosmetic powder to be loaded directly into the case itself. The second difference is that V3E has an applied dematerialisation rate of 17%. No dematerialisation rate whatsoever can be done on V3 as the case needs to be sturdy enough in order to withstand the high forces experienced during the blush powder packing process.

Results showed that V3 is more environmentally friendly than V3E, with the results varying with the percentage of recycling applied. This result is especially interesting when considering that the functional unit mass for both versions is essentially the same, since the lack of pans in V3 and the dematerialisation in V3 happened to cancel out each other in terms of product mass, as can be seen in Table 4. However, there are several factors that need to be considered before making a realistic decision regarding these two versions. It should be noted that V3 is in a league of its own and realistically is highly unlikely to be executed, since it requires significant changes in the supply chain and needs to be approved by the global cosmetic brand itself. However, the implications of this product design, i.e. eliminating the use of the pan, shows a lot of promise.

V1 vs V3

Another interesting take away can be observed when comparing V1 with V3(c) which shows a significant decrease in environmental footprint of 70%, which also happens to be the most environmentally friendly version when considering all the proposed versions. This proves that the main sustainability contributor to the entire cosmetic blush product is actually the pan. This is even more interesting when identifying that V1 requires only 1 case and 4 pans to satisfy the functional unit, while V3 requires 4 cases and adds 44.7 g of functional unit mass over V1. Yet despite all of this, V3(c) proved to be better than V1 due to the elimination of the pan.

This result makes sense when considering the environmental impact that aluminium (from which the pan is produced), has over the other elements of the case itself. When observing the CO_2 footprint impact per part, the highest contributor is the pan with 32 g, followed by the second worst contributor at 22 g associated with the lid. This comparison is even more significant when considering that the pan is 59% lighter than the lid in terms of mass, yet despite this contributes 10% more CO_2 than the highest mass component of the case assembly. This is also shown when considering the embodied energy aspect with the pan contributing

467 kJ, and the lid contributing to 603 kJ (Ansys (CES), 2021). However, when considering the mass difference of 59%, the 136 kJ embodied energy discrepancy is not really relative. In fact, if the pan is compared with a similar mass part such as the base which is only 7% heavier than the pan and is the same material as the lid, the embodied energy drops significantly to 263 kJ as opposed to the 467 kJ of the pan; a 44% discrepancy favouring the base part.

However, it should be noted that positive effects of V3 are only registered when a recycling rate of 100% is applied. Recycling rates of 0% and 50% proved to be much worse than the existing version, which once again makes sense since aluminium is proven to cause larger environmental impacts than ABS plastic, so if no recycling is applied the environmental impacts are much more significant.

3.3. Result summary

One primary result that can be observed is that the positive effect of reusability out ways by far the effects of dematerialisation by 171% when considering the human health endpoint (versions V1(a) vs V2). Another observation is that applying recyclability to a product that is already reusable, does not reduce the environmental impact by a significant amount, as indicated by the 13% decrease when considering the human health endpoint (versions V1(a) vs V1(c)). In contrast, applying recycling to a single use product, resulted in very large environmental savings of 92% when considering the human health endpoint, and 90% when considering the ecosystems endpoint (versions V2 vs V3(c)). It can therefore be concluded that the existing cosmetic blush compact performed extremely well when compared to the studied versions. The only argument that should be made when comparing the obtained results of V1(a) and V1(c), is that the recycling aspect throughout the entire study was considered only for plastic parts. This indicates that if the glass mirror and the aluminium pan could be recycled, the results would be far more significant than those registered in this study, especially when considering the large environmental discrepancy between ABS and aluminium, with aluminium having a 48% higher embodied energy and a 73% higher CO_2 footprint than ABS plastic (Ansys (CES), 2021). The only version which performed significantly better than the current scenario (V1) is the recyclable single-use version V3(c). In this version, the aluminium pan which enables the case to be reused was eliminated. The environmental benefits resulting from the removed pan and the recycling counteract for the lack of reusability of the product. However, had the modified compact not been recycled entirely at its End-of-Life, the positive effects of the removed pan would be counteractive. In fact, V3 (a-b) perform much worse than the benchmark scenarios V1(a-c).

4. Conclusions

There are a number of key takeaways which can be extracted from the LCA carried out in this study. The main takeaway is that reusable packages are very well suited when compared to the versions proposed in this research, even if the plastic waste is not recycled. Moreover, any potential improvements such as making the packages recyclable in conjunction with their reusability, were found to yield very little benefits. However, it was found that if packages are not reused, the impacts increase significantly.

When it comes to recycling, it was assumed that only the plastic components were recyclable. If the other components (more specifically the aluminium pan) were to be recycled as well, the generated results are expected to be significantly different. Moreover, there is potential to increase environmental benefits by an average of 74% across both endpoints when compared to the existing product, should the compact design be altered in such a way that the use of the pan is eliminated altogether, i.e. V3(c). This is due to the fact that the pan is made from aluminium, which has significant negative environmental impacts. The main difficulty here is that this change impacts the filler company the most, since with this proposed design it will not pack the cosmetic blush powder in the pan like previously, and instead will have to find a way how to load the blush powder directly into the plastic case or change the material to a more durable plastic. This raises strength and quality issues since the manufactured case would need to be extremely rigid and durable to withstand the cosmetic blush packing process. Finally, it can also be concluded that attempting to recycle the plastic case, but not recycling the aluminium pan due to contamination, proves to be almost ineffective due to the fact that aluminium has a high embodied energy and carbon footprint. Therefore, manufacturers should attempt to use materials with less harmful impacts and move towards reusable products comprising recyclable mono-materials.

4.1. Future work

One aspect for further research includes the possibility of changing the pan's material to be recyclable or biodegradable. As previously mentioned, aluminium pans contribute negatively to the overall sustainability of cosmetic packages. Therefore, altering the material of the pan to a more environmental option could greatly improve the product's environmental footprint. The main difficulty in this task, is that the alteration of the pan material falls under the filler's company responsibility, and not the compact manufacturer, meaning that this may prove difficult to get executed. Another possibility for future work would be to study the elimination of the use of the pan altogether. This will most likely require a new case design and will require comprehensive analysis and testing such as by utilising Finite Element Analysis and quality checks, to ensure that the case will be sturdy enough to withstand the powder packing process. Such a scenario does not really fall within the plastic manufacturer's remit. However, this should be researched further and potentially trialled in collaboration with the powder filler companies, in order to identify if it would actually be viable and feasible to do so.

CRediT authorship contribution statement

Isaac Jordan Gatt: Conceptualization, Methodology, Validation, Formal analysis, Software, Investigation, Data curation, Writing – original draft, Visualization. **Paul Refalo:** Conceptualization, Methodology, Validation, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition, Resources.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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